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We have been investigating the design of next generation mobile wireless networks that employ no existing infrastructure to aid the communications process. We have developed new mechanisms for providing such networking services and for configuring such (ad hoc) wireless network systems through our innovative development of the Mobile Backbone Network (MBN) concept. Backbone Capable Nodes are dynamically elected to serve as Backbone Nodes (BNs), based upon their location, radio communications reach and communications and processing capacities. Using the BNs, backbone networks (BNets) automatically self configure under unit movements and adapt to changes in communications conditions. When available, UVs (Unmanned Vehicles) serve to form and connect BNets. A backbone node is used to manage its access network (ANet). The latter serves to provide access to the network of regular nodes or of gateway nodes.

We have been developing techniques for the topological synthesis of mobile backbone networks. We have been developing new methods (identified as MPLS+) for effective networking and routing of messages across backbone networks when the processes implemented by the nodal routers must be simplified due to their capacity, size and power constraints. We have been evaluating and synthesizing such networks under the loading of highly bursty traffic processes, modeled as multifractal stochastic processes. We have also been developing new medium access control (MAC) algorithms for access networks feeding our MBN architectures.

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Design and Analysis of Mobile Backbone Networks

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Table of Contents

Abstract

We have been investigating the design of next generation mobile wireless networks that employ no existing infrastructure to aid the communications process. We have developed new mechanisms for providing such networking services and for configuring such (ad hoc) wireless network systems through our innovative development of the Mobile Backbone Network (MBN) concept. Backbone Capable Nodes are dynamically elected to serve as Backbone Nodes (BNs), based upon their location, radio communications reach and communications and processing capacities. Using the BNs, backbone networks (BNets) automatically self configure under unit movements and adapt to changes in communications conditions. When available, UVs (Unmanned Vehicles) serve to form and connect BNets. A backbone node is used to manage its access network (ANet). The latter serves to provide access to the network of regular nodes or of gateway nodes.

We have been developing techniques for the topological synthesis of mobile backbone networks. We have been developing new methods (identified as MPLS+) for effective networking and routing of messages across backbone networks when the processes implemented by the nodal routers must be simplified due to their capacity, size and power constraints. We have been evaluating and synthesizing such networks under the loading of highly bursty traffic processes, modeled as multifractal stochastic processes. We have also been developing new medium access control (MAC) algorithms for access networks feeding our MBN architectures.

Chapter I: Summary

Research Developments

We have been investigating the design of next generation mobile wireless networks that employ no existing infrastructure to aid the communications process. We have developed new mechanisms for providing such networking services and for configuring such wireless network systems (also known at times as ad hoc networks) through our innovative development of the Mobile Backbone Network (MBN) concept. Our network architecture resembles that of a cellular network system, in that we employ Backbone Nodes that have similar functionality to that provided by base stations for cellular wireless networks. For the latter, a mobile user associates itself with the nearest base station, using the latter to collect its messages and to deliver to it mobile-oriented messages. In turn, our system employs no fixed stationary base station nodes, so that nodes must be automatically selected to act as backbone nodes (serving the role of base stations) based upon their location, radio communications reach and communications and processing capacities.

We also manage unmanned ground vehicles (UGVs), such as robot units, which we guide to desirable locations to serve as backbone nodes in areas that require communications access support.

Our developments of mechanisms, techniques, analysis, management and design methods for mobile backbone wireless networks are of significant importance. These networks are planned for employment in situations where no networking infrastructure exists so that a wireless network system must be rapidly configured. This involves a wide range of critical networking scenarios. Included are homeland security , disaster relief, and emergency support network systems that must be self-configured and operated under conditions in which the underlying networking backbone may have failed or been destroyed. Also included are situations under which the operation takes place in remote places that do not have a communications networking infrastructure. As such, these networks also serve as key architectures for the design and operation of next generation military network systems. Also of key interest is the implementation of these systems for interconnecting remote residential and business locations, providing also for remote learning and telemedical services, noting the latter to often lack a communications backbone infrastructure.

Our activities include:

1. Research into backbone based wireless networks.
2. Extesnive simulations of backbone based ad hoc wireless networks
3. Writing of research papers and presentations at conferences, workshops and meetings
4. Educational activities for graduate students at UCLA in the area

of research.
5. Educations activities for undergraduate students at UCLA, through involvement in our research activities, developments of simulations runs, participation in project reviews, involvement in network design and analysis efforts.

Research Results

We have obtained a wide range of significant results for the design and analysis of mobile wireless networks based on our unique MBN architecture. A number of key developments are noted in the following:

a. We have developed MBN network architecture as consisting of multiple hierarchies. Backbone networks (BNets) automatically self configure under unit movements and adapt to changes in communications conditions. When available, UVs serve to connect BNets. A BNet consists of capable backbone nodes. A backbone node is used to manage its access network (ANet). The latter serves to provide access to the network of regular nodes or of gateway nodes. A gateway node provides communications interworking between the mobile backbone network and an Application Specific Private Network (ASPN). The latter involves an autonomous network system that operates on its own in accordance with its unique protocols and must at times interconnect through its gateway with other networks. Examples of ASPNs include sensor networks (employed to collect data concerning the underlying environment in which they reside), home/airport/campus networks, local area networks (such as those using wireless media), and very short range networks (such as Bluetooth driven networks that are used to connect devices at very short range, including human outfitted instruments, and medical support networks).

b. We have been developing techniques for the topological synthesis of mobile backbone networks. Our algorithms serve to automatically elect nodes to perform as backbone nodes and to form interconnections with other backbone nodes to synthesize a capable backbone network. Our algorithms provide for automatic self-configuration of backbone networks upon element failures, communications links interferences and under connectivity changes induced by nodal mobility.

c. We have been developing new methods for effective networking and routing of messages across backbone networks when the processes implemented by the nodal routers must be simplified due to their capacity, size and power constraints. For this purpose, we have developed a new routing and switching methodology, identified by us as MPLS+. It extends standardized MPLS (Multiple Protocol Label Switching) techniques to yield an operation that requires routing tables with significantly reduced sizes. Such methods are also used to guarantee quality of service (QoS) performance to network flows. In this manner, real-time streams such as voice and video flows can be supported at high fidelity.

d. We have been investigating algorithms for the formation of ANets.
We have been developing new protocols for nodes to automatically and dynamically associate themselves with backbone nodes.

e. We have invented a new class of hybrid networking and Medium Access Control (MAC) resource allocation techniques for the operation of ANets. Using these protocols, users are assigned ANet resources (including time slots, frequency bands and/or CDMA codes). Their power levels are regulated, so that they can transmit their messages to their associated backbone nodes in a timely basis.
f. We have investigated the performance of our random-access data and control channels when loaded by highly bursty traffic processes that exhibit long range dependence.
g. We have studied wireless network systems that support data message transport for fast moving users.

Our developments provide major technological innovations that are necessary to implement the next generation operation of high fidelity self-configuring mobile wireless networks that provide us automatic access to key networked support services, anywhere and anytime.

Training and Development

Research and teaching skill development in the design and analysis of wireless network systems; in the development of medium access control (MAC) algorithms that support quality-of-service (QoS) requirements for message flows; learning to synthesize and adapt the topological layout of mobile backbone networks that support mobile users across wireless media.

Researchers and students have learned methods for the design of a new generation of radio networks that support mobile users when no fixed infrastructure (such as that constructed for cellular wireless networks using base stations and the public telephone network)is available. Methods for fast re-configurability, resource allocations and QoS network management are developed and taught.

Among the many undergraduate, graduate and post-graduate students and researchers trained through this project, we mention the following:

Postgraduate and Ph.D.students:
- Dr. Jianbo Gao
- Dr. Shervin Shambayati
- Dr. Shai Benjamin
- Dr. Jing Ling

Ph.D. students:
- Arash behzad
- Laura Ju
- Kevin Xiaolong Huang
- Charles Yichen Liu
- Runhe Zhang
- Rima Khalaf
- Patrick Vincent

MS Students:
- H. Luo
- Eric Caballero

Undergraduate students:
- Andy Lo
- Stephen Shum
- England Wei.

Outreach Activities

We have been giving presentations and simulation-based demonstrations of our new developments for wireless networks that use autonomous (unmanned, ground and airborne) vehicles (robots)in areas where no networking infrastructure is present. These presentations were made in conferences, workshops, military and commercial organizations, and to student organizations.

Included are presentations that were made at the Pentagon, and to US Army development personnel, including to Col Steve MacLaird (JTRS JPO Dir), to ARMY contractors at Boeing working on the FCS and JTRS programs, and many others. They have recognized our approaches to form a basis for the design of next generation military network systems.

Journal and Conference Proceedings Publications

In addition to the annual technical reports submitted to ARO, we have contributed the following journal and conference publications. In Chapter 2, we present recent results involving our topological layout mechanisms for mobile backbone networks (MBNs).

1. Jianbo Gao and Izhak Rubin, "Multiplicative multifractal modeling of Long-Range-Dependent network traffic", *International Journal of Communication Systems*, vol. 14, (2001), p. 783.
2. Jianbo Gao and Izhak Rubin, "Multiplicative Multifractal Modeling of Long-Range-Dependent (LRD) Traffic in Computer Communications Networks", *Nonlinear Analysis*, vol. 47, (2001), p. 5765.
3. Jianbo Gao and Izhak Rubin, "Multifractal modeling of counting processes of Long-Range-Dependent network Traffic", *Computer Communications*, vol. 24, (2001), p. 1400.
4. Jianbo Gao and Izhak Rubin, " Analysis of Random Access Protocol under Bursty Traffic", *Proceedings 4th IFIP/IEEE International Conference on Management of Multimedia Networks and Services, MMNS 2001, Chicago, IL, USA, October 29 - November 1, 2001, Lecture Notes in Computer Science 2216 Springer 2001.*, (2001).
5. Izhak Rubin and Patrick Vincent, " Topological Synthesis of Mobile Backbone Networks for Managing Ad Hoc Wireless Networks", *Proceedings 4th IFIP/IEEE International Conference on Management of Multimedia Networks and Services,*

MMNS 2001, Chicago, IL, USA October 29 - November 1, 2001, Lecture Notes in Computer Science 2216 Springer 2001., (2001).
6. Shai Benjamin and Izhak Rubin, "MPLS+:A Scalable Label Switching Network", *Proceedings of IEEE GLOBECOM 2001, San Antonio, Texas, Nov. 2001.*, (2001).
7. Izhak Rubin and Jing Ling, "Delay Analysis of All Optical Packet Switching Ring and Bus Communications Networks", *Proceedings of IEEE GLOBECOM 2001, San Antonio, Texas, Nov. 2001.*, (2001).
8. I. Rubin, A. Behzad, R. Zhang, H. Luo and E. Caballero, "TBONE: A Mobile Backbone Protocol for Ad Hoc Wireless Networks", *Proceedings 2002 IEEE Aerospoace Conference, Big Sky, Montana, March 2002.*, (2002).
9. Jianbo Gao and Izhak Rubin, "Performance of Random Multiple Access Scheme Under Long-Range-Dependent Traffic", *Proceedings of IEEE International Conference on Communications (ICC'2002)*, (2002).
10. I. Rubin and A. Behzad, "Cross Layer Routing and Multiple-Access Protocol for Power Controlled Wireless Access Nets", *Proceedings IEEE CAS Workshop on Wireless Communications and Networking, Pasadena, CA, Sept. 2002.*, (2002).
11. S. Benjamin and I. Rubin, “Connected Disk Covering and Mobile Gateway Placement in Ad Hoc Networks,” *Proceedings of ADHOC-NOW Conference*, University of Toronto, Toronto, Canada, September 2002.

Chapter 2:

A Distributed Stable Backbone Maintenance Protocol for Ad Hoc Wireless Networks

Abstract—**We have recently introduced a hierarchical structure for ad hoc wireless networks that classifies nodes into Backbone Capable Nodes (BCNs) and Regular Nodes (RNs). Under our TBONE protocol, a backbone network (Bnet) is formed by dynamically electing Backbone Nodes (BNs) among BCNs. However the current TBONE protocol requires global topological information to elect and de-elect BNs, which can induce high control message overhead and slow down the Bnet layout adaptation process. In this paper, we resolve this problem by proposing a modified MBN Protocol (MBNP) for electing and de-electing BNs, which requires each candidate node to employ only local connectivity information (within two hops). While such schemes tend many times to be unstable, we prove and demonstrate that our process involving BN-BCN conversions is oscillation free. We show that the synthesized network configuration demonstrates desirable robustness and connectivity features, while demanding low control message overhead. Key performance characteristics of the modified protocol are exhibited by conducting simulation-based evaluations.**

1. INTRODUCTION

We have recently been investigating the operation of mobile wireless networks through the embedded establishment of a Mobile Backbone Network (MBN). In [1], we have defined the structure and elements of mobile backbone based ad hoc wireless networks and presented a protocol (TBONE) for the synthesis of MBNs. In [2]-[3], we have examined several approaches pertaining to the topological synthesis of mobile backbone networks. In [4], we have presented algorithms for the construction of a connected backbone network that covers mobile nodes, whereby the backbone nodes (gateways) were moved (guided, or autonomously moved into position as unmanned or manned vehicles) into proper positions. A medium access control (MAC) layer protocol for access nets, employing power-control spatial-reuse demand-assigned TDMA (or FDMA/CDMA) is presented by us in [5].

A mobile backbone network consists of a backbone network (Bnet), access nets (Anets), and regular (flat) ad hoc network(s). Its structure is illustrated in Figure 1. Thick solid lines connecting large solid circles represent the Bnet. Dashed ovals consisting of thin solid lines connecting small solid circles represent the Anets. The small solid circles and the thin dashed lines connecting them to each other represent the regular ad hoc

network. In this paper, we concentrate on protocols governing the operation of the MBN's Bnet. The MBN is designed so that it involves a sufficient but not excessive number of backbone nodes, while providing high coverage, so that a high fraction of the low power nodes can access at least a single Backbone Node (BN) through 1 hop.

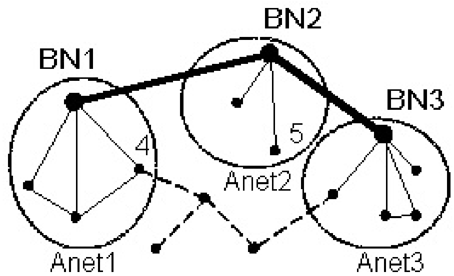


Fig. 1- The decomposition of a mobile backbone network into a Bnet, three Anets, and a regular ad hoc network with h=1 and k=1

We identify two key classes of elements in our MBN system: high capacity nodes and low capacity nodes. High capacity nodes can serve as either Backbone Nodes (BNs) or Backbone Capable Nodes (BCNs). They have high storage and processing resources, and include low power and high power radio modules that allow them to transmit/receive data and control messages in two different frequency bands simultaneously. The low power radio module is used to communicate to nodes that are in low-power communications range while the high power radio module is employed by a BN to communicate to its peer BNs (across the Bnet, spanning longer distances and operating at higher data rates). When a high capacity node is serving as a BCN, it will continuously and simultaneously listen for messages transmitted in its reception range across the two frequency bands. However, it *only* uses its high power radio module for receiving and transmitting control packets. A BCN has the capability to be converted into a BN, when selected to act as a BN by our protocol. Low capacity nodes act merely as Regular Nodes (RNs). RNs are limited in their power, storage, processing and communications assets and only employ a single low power radio module.

In this paper, we propose a modified MBN protocol (MBNP). This protocol includes the RN association algorithm, and the BN-to/from-BCN conversion algorithm. Through these three algorithms, we try to reduce the number of BNs to maintain Bnet connectivity under varying mobility conditions. The performance and stability of our protocol is shown by simulation.

The later sections are organized as follows: In Section 2, a new BCN-to-BN conversion and BN-to-BCN conversion protocol are designed. In section 3, we prove that our proposed protocols are oscillation free. In section 4, simulation results are given to show the stability of the protocol. We finally conclude in Section5.

2. BCN-BN Conversion and BN-BCN Conversion Protocol

We are initially faced with a regular ad hoc network composed of Backbone Capable Nodes (BCNs) and Regular Nodes (RNs). Backbone Nodes (BNs) should be selected among Backbone Capable Nodes gradually to form a Mobile Backbone Network. Some of BNs should be deselected to be BCNs to reduce the network resource consumption, such as energy and control message overhead.

A BCN-to-BN (also denoted as BCN-BN) conversion algorithm is introduced in [1] to elect BNs among BCNs. In the proposed BCN-BN conversion algorithm, an unassociated BCN periodically broadcasts its node ID and dynamic weighted label to its one hop neighbors using its low power transmission module. An unassociated BCN will convert itself to a BN, if its dynamic weighted label is the highest among all its unassociated BCN neighbors. A BCN will also be converted to a BN, if there is no finite hop path between two of its neighbors. The purpose of the conversion is to connect disjoint backbone components. But unfortunately, to check whether there is a finite hop path between two nodes requires the node be aware of the global topology information, which induces significant control message overhead and makes the backbone network less adaptive to the topology change.

In this paper, both BN-to-BCN (also denoted as BN-BCN) as well as BCN-to-BN (also denoted as BCN-BN) conversion protocols are introduced, that only require a node be aware of local topology information within two hops for the decision of BCN-to-BN and BN-to-BCN conversions. These two protocols work concurrently to prevent the occurrence of frequent BN-to-BCN and BCN-to-BN oscillations and to reduce the number of required active BN nodes (thus contributing to energy conservation).

We start by defining the new BCN-to-BN conversion protocol.

BCN-to-BN Conversion Protocol

Definition 1: There is said to be an n hop path between bn_a and bn_b, if there exists a route $[bn_a, bn_0, bn_1, \ldots, bn_k, bn_b]$, where $k=n-2$. The path length is said to be n.

Under the BCN-to-BN conversion protocol, every BCN node periodically broadcasts *hello* messages to its one-hop neighbors. For instance, a BCN bcn_1 periodically reads its neighbor list ngl_1. This list is composed of the low power RN neighbors of bcn_1 and the high power BCN/BN neighbors of bcn_1. Node bcn_1 will convert itself to a BN if any of the following conditions is satisfied:

1. There exists an RN neighbor $rn_i \in ngl_1$ which has no BN neighbors.
2. All three conditions are satisfied:
   a) bcn_1 is unassociated.
   b) bcn_1 has at least one unassociated BCN neighbor.
   c) bcn_1 has the highest dynamic weighted label among all its BCN neighbors.
3. The following two conditions are satisfied:
   a) bcn_1 is associated.
   b) There exists a BCN neighbor $bcn_i \in ngl_1$, which has no BN neighbors.
4. There exist two BN neighbors, bn_a and bn_b, where there is NO path between bn_a and bn_b, whose path length m is smaller than or equal to $d1$, so that $m \le d1$

Condition 1 forces a BCN to be converted to a BN when it has at least a single RN neighbor that cannot associate with any current BNs. This condition expands the backbone node population to admit (i.e., associate) more unassociated RNs into the MBN.

Condition 2 provides for the conversion of a BCN into a BN from a group of unassociated BCN neighbors. This condition is identical to a corresponding one specified for the previously proposed BCN-to-BN conversion algorithm.

Condition 3 forces an associated BCN to convert to a BN when at least one of its BCN neighbors cannot associate with any BN. This condition expands the backbone node population to connect (i.e., associate) more unassociated BCNs into MBN.

Condition 4 induces a BCN to convert to a BN, when the path length between at least two of its neighbors is greater than *d1*. As a special case, When the BCN has two BN neighbors that belong to separate network components (i.e., to disconnected sub-networks, so that there exists no path connecting these two BNs), the converted node will serve to connect these two components. This conversion from BCN to BN improves the MBN's topological connectivity by adding a new (shorter) path, as well as serves to potentially decrease the network's graph diameter.

Figure 2 shows the scenarios for the four conditions.

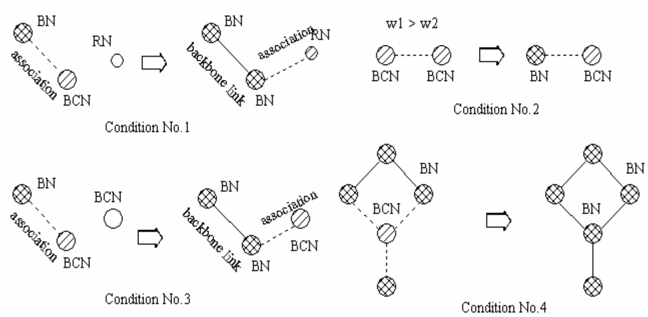


Fig.1 BN Election Conditions

When *d1* is set to be 2, only local topology within 2 hops is required to check the condition. For the proposed Condition 4 to work properly, a BCN only needs to obtain the neighbor list of neighbors to test Condition 4. Consequently, neighbor list messages are only locally broadcasted, thus avoiding wider scope flooding of these messages (and consequently reducing the control overhead level).

In the following, we present the Local Connectivity Detection Algorithm that is used to test for the occurrence of events that induce Condition 4 to hold.

Local Connectivity Detection Algorithm (LCD)

```
Begin
Find all the neighbors of node n1;
  if ( no neighbor )
    return( Condition 4 false )
  else
    for ( each of n1's neighbor ni )
      add ni and ni's neighbor to an array Ai
    if ( more than one neighbor of n1 )
      if ( each pair of arrays, Ai and Aj,  have at least one common member )
        return(Condition 4 true)
      else
        return(Condition 4 false)
    else
      return (Condition 4 true)
  endif
```

16. END

BN-to-BCN Conversion Protocol

A BN-to-BCN conversion protocol is designed in this paper to reduce the population of BNs in the MBN, while at the same time maintaining the connectivity of the backbone network. In general, a reduction in the BN population will lead to lower energy consumption. In the following, we present our modified BN-to-BCN conversion algorithm, as well as prove that it does not lead to an oscillatory BN-to/from-BCN conversion process.

BN-to-BCN Conversion Protocol

The following messages are transmitted by a BN under the BN-BCN conversion protocol.

Message *alert*: This message contains the ID of the BN. It is flooded to its 2-hop neighbors to alert other BNs that a BN-BCN conversion process is planned.

ID field *conversionID*: The ID field is to inform the BN whether it is legal to convert.

Timer *tmr*: The timer is used to delay the conversion of a BCN.

The algorithm is outlined below:

1. Begin
2. A BN bn_1 will check whether the following conditions are simultaneously satisfied.
   a) Condition 1: Each low power RN neighbor of bn_1 has at least one BN neighbor in addition to bn_1.
   b) Condition 2: One of the low power neighbors of bn_1 is a BN.
   c) Condition 3: Each low power BCN neighbor of bn_1 has at least one BN neighbor in addition to bn_1.
   d) Condition 4: For each pair of two high power BN neighbors of bn_1, say bn_a and bn_b , once this BN is converted, there is a path between bn_a and bn_b, whose length m is smaller than or equal to $d2$ hops, $m \leq d2$. In our protocol, $d2$ is set to be 2.
3. If all the conditions stated above are satisfied, then:
   a) Set a timer to an expiration time of *tmr* to be large enough to permit sufficient time for the reception of *alert* messages from BNs that are two hops away.
   b) Set *conversionID* to be bn_1.
   c) Send an *alert* message.

   Otherwise, stop the conversion process.
4. While the time for *tmr* has not expired, set *conversionID* to be bn_2, upon receiving an alert message from bn_2, whose ID has a greater value than the ID value of bn_1.
5. If *conversionID* displays the ID of bn_1 at the end of the *tmr* period and Condition 3 holds, bn_1 converts itself to a BCN. Otherwise, the process is canceled.
6. End

In the following, we explain the above stated BN-to-BCN conversion algorithm. When bn_1 intends to convert itself to a BCN, an *alert* message with a hop count 2 is sent,

it is marked with the ID bn_1. A timer is set to an expiration time *tmr* that is large enough to permit sufficient time for the reception of *alert* messages from BNs that are two hops away. If an *alert* message is received by bn_1, whose ID field value is greater than the ID field value of bn_1, the conversion process is canceled to prevent simultaneous conversions.

Condition 1 ensures that this BN will be potentially able to associate with another BN, if this BN is converted to a BCN.

Condition 2 and 3 ensures all the RN and BCN neighbors of this BN will be potentially able to associate with another BN, if this BN is converted to a BCN.

Condition 4 is the main trigger of the BN-BCN conversion process. The objective of Condition 4 is to ensure that once this BN is converted, the distance between any two neighboring BNs of this BN will not degrade below its current level (which is equal to 2, as they are connected to each other through this BN). We prove in a later session that Condition 4 ensures that BCN-to-from-BN conversions do not exhibit oscillatory behavior. Condition 4 is tested by using the Local Connectivity Algorithm presented in the previous subsection.

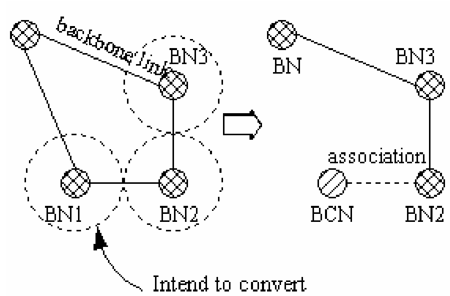


Fig.3 BN-BCN Conversion

The timer and the alert message avoid uncoordinated simultaneous BN-to-BCN conversions to occur in the following case. Figure 3 illustrates a case under which BN1, BN2, and BN3 consider at the same time to convert to BCNs. Through the coordinated use of *alert* messages, only one of the BNs will actually decide to convert to a BCN.

3. BN TO/FROM BCN OSCILLATIONS

Definition 2: We represent the backbone network topology as a graph *G(V, E)*, where *V* is the set of all the BNs in the MBN and *E* is the set of all the high power links between two neighbor BNs.

Definition 3: A node is said to experience BN to/from BCN oscillations if, over a finite period of time during, the node repeatedly converts between BN and BCN roles.

Definition.4: A protocol that results in no BN to/from BCN oscillations is said to be an oscillation free protocol.

Because of the distributed nature of the protocol, network BN and BCN nodes determine whether they should initiate a conversion process by using local status information, as they do not have access to global information and to performing network-wide cooperation. Consequently, a larger than desired number of BCNs (needed to

sustain backbone network connectivity) may convert themselves to BNs. Subsequently, some of these BNs may be declared redundant (to reduce the number of BNs, improving energy conservation) and thus convert back to BCNs. This process can repeat, leading to oscillations. The BCN-to/from-BN conversion protocol should prevent such BN-to/from-BCN oscillations, leading to a backbone network virtual topology that is stable under static conditions (so that the conversion algorithm converges in a finite number of steps). In the following, we prove that our proposed BCN-to/from-BN conversion protocol with the preserved window phase is oscillation free.

Lemma 1: Given a stationary network topology, the BN-BCN conversion protocol presented above does not trigger the reverse conversion of this node to a BN, and it does not trigger the conversion of another BCN to a BN, when $d1 \geqslant d2=2$.

Proof: Assume node $n1$ converts from BN to BCN.

Because Condition 1 of BN-BCN conversion for $n1$ holds, Condition 1 of BCN-BN conversion for $n1$ does not hold. Because Condition 2 of BN-BCN conversion for $n1$ holds, Condition 2 of BCN-BN conversion for $n1$ does not hold. Because Condition 3 of BN-BCN conversion for $n1$ holds, Condition 3 of BCN-BN conversion for $n1$ does not hold.

Because Condition 4 of BN-BCN conversion for $n1$ holds, the distance of the path between any two BN neighbors of $n1$, say n_i, n_j, should be less than or equal to 2 ($d2$=2) without the aid of $n1$. Assume two BN neighbors of BCN node $n2$ are n_x, n_y. If the distance between n_x and n_y before $n1$'s conversion is $m1$, after $n1$'s conversion, for the distance between n_x and n_y, say $m2$, we have $m2 \leq m1$. It means, if $m1 \leq d1$, we have $m2 \leq d1$. Thus when $d1 \geqslant d2=2$, Condition 4 of BCN-BN conversion for $n1$ and $n2$ does not hold.

■

Theorem 1: Given a stationary network topology, the two-hop based BCN to/from BN conversion protocol is oscillation free.

The proof (omitted here) uses the following result:

Lemma 2: Between any two update periods of the set, if a node in the set converts from BN to BCN, it will not convert back to BN.

Corollary 1: Given that initially no BNs are present, and assuming static conditions (i.e., no location changes), the final status (BCN or BN role) of high capacity network nodes is reached in a finite period of time.

These results prove that the backbone maintenance protocol presented here induces a stable (BN-to/from-BCN conversion process based) operation.

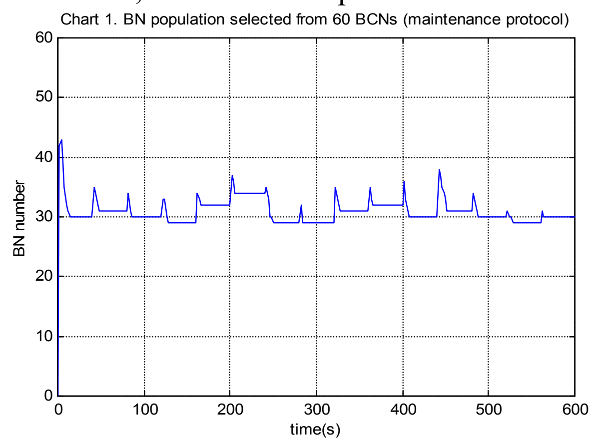
4. Simulations

We have conducted simulations for testing the oscillatory features of the proposed protocols and to evaluate the protocol overhead. We have set $d1=d2=2$, so that only local topological information is required for BCN-BN and BN-BCN conversions.

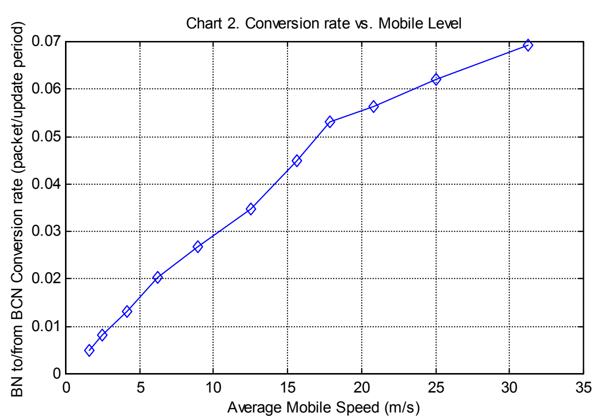
The simulation parameters are as follows:

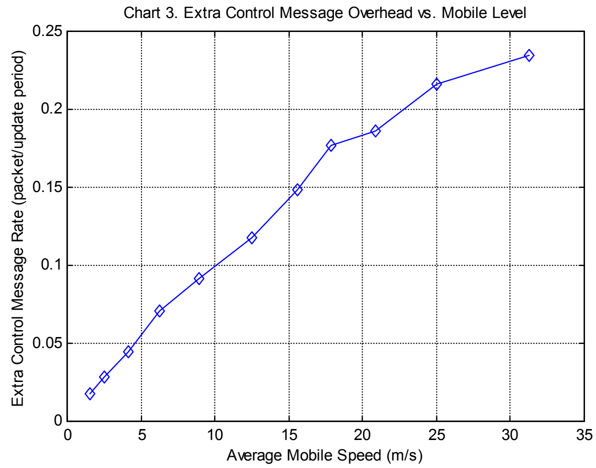
Area	Low power range	High power range	Connectivity update time
1600m×1600m	250m	500m	1s

A scenario that contains 60 BCNs and no RNs was examined. The topology is changed every 40 seconds; it was maintained static each 40 seconds period. The BN population under this maintenance protocol is plotted in Chart 1. It shows the BN population to be oscillation free, for each static period.



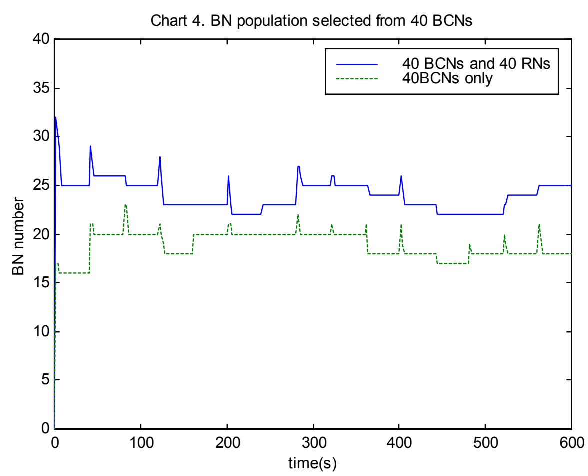
Under a scenario that contains 60 BCNs and no RNs, the conversion rate of BN to/from BCN per node versus the average mobility speed level is examined. The results are shown in Chart 2. It confirms, as expected, that when the mobility level drops the conversion rate per node is reduced.





The excess control overhead (defined as the protocol's control overhead rate excluding the periodically conducted connectivity updates that are carried out at a rate of 1 'hello' message /sec) of the protocol per node versus the average mobility speed level is examined under a scenario that contains 60 BCNs and no RNs. The result is shown in Chart 3.

Another scenario with 40 BCNs was examined to demonstrate the influence of including RNs. The result is shown in Chart 4. When 40 RNs are added into the topology, more BCNs are required to convert themselves to BNs to cover the inserted RNs.



5. Conclusions

In this report, a stable backbone maintenance protocol is introduced and studied for mobile backbone network (MBN) based ad hoc wireless network architectures. This protocol serves to elect Backbone Nodes (BN) among Backbone Capable Nodes (BCN) and convert BNs back to BCNs to reduce the active BN population, leading to energy and

BN resource conservation. The conversion from BCNs to BNs is used to construct backbone networks that have desired connectivity features. The conversion from BNs to BCNs is used to reduce the BN population, as noted above, while maintaining the desired connectivity level of the backbone network. Our new protocol is shown to yield an oscillation free conversion process, for a static topological configuration.

To implement a simpler and faster adaptive distributed operation for the conversion process, which also induces lower control overhead rates, the protocol presented in this paper requires each node to collect connectivity information from nodes that are only two hops away. For a greater reduction in the number of actively elected backbone nodes, the network designer may wish to allow weaker requirements for connectivity degradations that may occur under such conversions. Such protocols are similarly specified, and are currently under investigation.

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